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SHORT-WAVELENGTH PERTURBATION GROWTH STUDIES FOR NIF DOUBLE-SHELL IGNITION TARGET DESIGNS.

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Abstract. A major challenge in achieving ignition with double-shells is controlling the mix of the dense, high-Z pusher into the DT gas. During implosion, interface perturbations become unstable as they are subjected to either impulsive (Richtmyer-Meshkov) or time-dependent (Rayleigh-Taylor) accelerations. These processes are especially critical for double-shells since density gradient stabilization mechanisms (that play a key role in the baseline cryogenic target) are not present. To study the nonlinear RT evolution for such a large range in modes we use the parallel 3-D rad-hydro code HYDRA. Simulations have revealed a new pathway for the RT instability of perturbations on the outer surface of the inner shell leading to shell disruption. We demonstrate that this instability can be controlled by tamping the inner shell with a low-Z material but it is not entirely suppressed. We find that the pusher/tamper interface transitions to turbulence at late times with large Reynolds number but still the integrity of the pusher is maintained. Furthermore, numerical studies suggest that for perturbations with mode numbers ($l > 600$), the mix-width at the pusher/tamper interface approaches a constant value. Finally, to avoid turbulence onset altogether we investigate a new pusher with an imprinted density-gradient scalelength in combination with a CuO/Cu_2O foam. Preliminary 2-D simulations with mode numbers up tp $l = 612$ show virtually no growth in this design.

I. INTRODUCTION

To maximize the prospects for achieving ignition on the National Ignition Facility (NIF) consideration of complementary designs to the cryogenic baseline target is desirable. Double-shell (DS) targets were dismissed in the late 70's and early 80's due to poor performance and not well-understood hydrodynamic behavior. Many advances have ocurred in the last two decades and while obtaining high gain with DS targets is still a daunting task, the requirements of non-cryogenic preparation and simple laser pulses justifies a renewed effort using state-of-the-art computational and experimental techniques. Two campaigns are currently underway. The first is an experimental effort at the Omega laser facility, using ignition-like DS targets designed to develop greater understanding of the performance issues of an ignition DS. The other is computational, using the latest massively parallel architectures in an attempt to directly simulate instabilities of short-wavelength perturbations, commonly speculated to be the major source of performance degradation.

The renewed experimental effort began by testing a conjecture by Varnum *et al.*[1] attributing DS poor performance to asymmetries in the M-band radiation coming from the hohlraum laser hot spots. Recently, Amendt *et al.*[2] performed experiments geared to test the performance scaling with the fall-line parameter.[a] Both experiments yield satisfactory results indicating that an increased understanding of DS implosions is emerging.

Computational efforts, aiming to improve the margin on the deleterious effect of mixing high-Z pusher material with hot DT fuel, were carried out by Amendt *et al.*[3] Their calculations only captured the gross features of a DS implosion and stopped short of addressing large mode number instabilities at material interfaces. These are critically important for the DS, since normal stabilization processes, such as density gradients, vorticity dissipation and mass diffusion, are either absent or only effective in controlling the growth of exceedingly large mode number perturbations (> several thousands). Here, we use the state-of-the-art code HYDRA[4] to investigate the effect of short wavelength perturbations on DS implosions. Previously[5], we reported on a new pathway for the Rayleigh-Taylor (RT) instability of perturbations present on the outer surface of the inner shell that may lead to shell breakup and quench ignition. Alternative designs obtained by introducing a tamping material on the outer surface of the inner shell control the instability to tolerable levels but do not entirely suppress it. In this paper we further develop our understanding of the hydrodynamic behavior of the pusher/tamper interface, by characterizing the late time behavior of the instability. We find that the flow at the pusher/tamper interface becomes turbulent with large

[a] The fall-line is the trajetory that material at the fuel-pusher interface would follow in the absense of deceleration. The fall-line parameter is defined as the difference between the time of peak burn and the time the fall-line reaches the origin, normalized to the full-width half-maximum burn history.

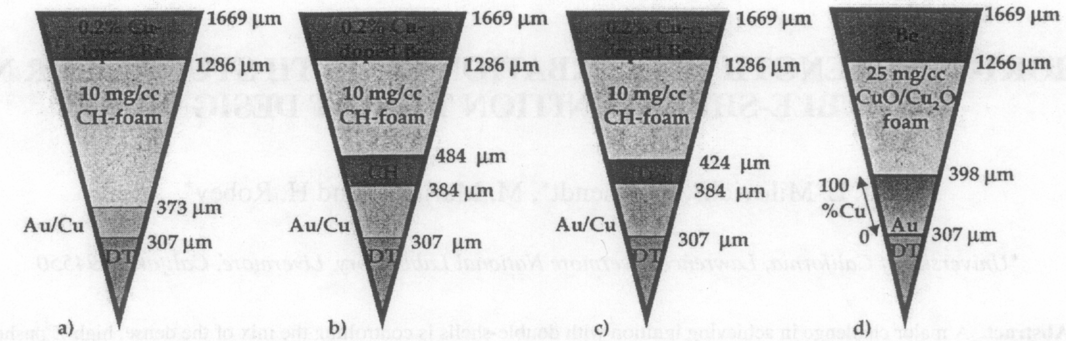


FIGURE 1. Schematic of NIF double-shell ignition designs: a) originally proposed by Amendt *et al.*[3] b) modified with 100 μm CH-tamped inner shell c) modified with 40 μm Ti-tamped inner shell d) Cu-graded inner shell raging from 0% Cu on the inner side to 100% at the outer surface and CuO/Cu_2O foam.

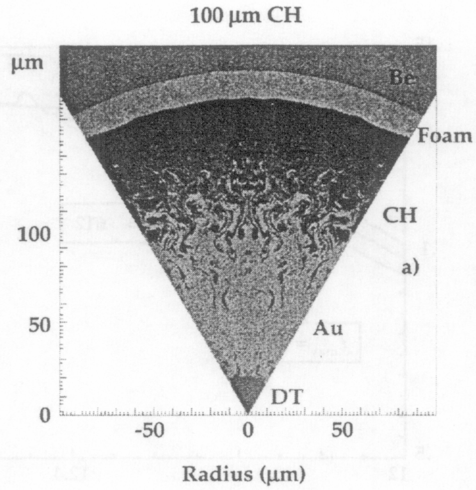
Reynolds number. We also find that the extent of the mixing layer that develops remains bounded, encompassing only 40% of the pusher. However, the ability to study this phenomenon by direct numerical simulation is curtailed by the current limitation in computer resources. To model the Kolmogorov length scales will require prohibitively large computational times forcing us to use qualitative arguments to understand DS implosions. To eliminate this apparent hurdle we are exploring the possibility of substantially reducing the instability by explicitly imposing a density gradient scalelength by direct manufacting on the outer surface of the pusher. This technique has been successfully employed in the baseline design where a frozen fuel layer lies between the main fuel and the ablator. Preliminary 2-D simulations indicate that the reduction in the growth factors introduced by the density gradient substantially reduces the possibility of shell breakup.

II. SIMULATION STUDIES

A schematic cross-section view of the proposed ignition DS target is shown in Fig. 1a. The outer shell (ablator) consists of a Cu-doped Be, with a 0.2% dopant concentration chosen to minimize the penetration of high energy radiation from the hohlraum wall. The inner capsule is made of Au-Cu and encloses a high pressure DT gas at 700 atm. To understand the effects of short wavelength perturbations we have systematically introduced perturbations in the different material interfaces and found that the outer surface of the pusher is highly unstable to RT instability well before deceleration onset. This instability is attributed to the large outward expansion of the outer surface of the pusher due to the high-energy L-shell x-rays (> 8 kev) penetrating through the ablator. As the imploding outer shell recompresses this material a density jump of ≈ 4 (Atwood number ≈ 0.7) is established at the pusher/foam interface which is accelerated through a longer distance resulting in large RT growth. Our studies revealed that perturbations containing mode numbers larger than $l > 200$ are able to disrupt the inner shell and quench ignition.

To control this instability we have introduced an additional material layer on the outer surface of the pusher. The thickness of the layer was carefully determined by extensive 1-D simulations utilizing two tamping materials: CH and Ti. An schematic view of the optimum NIF designs is presented in Figs. 1b,c. Two-dimensional simulations of these two new designs were performed in a 30° wedge with perturbations on both pusher/tamper and tamper/foam interfaces. The initial perturbation, containing modes up to a maximum $l_{max} = 816$,[b] was drawn from a measured Omega glass capsule spectrum with root-mean-square ≈ 3 nm. Results near ignition time for both CH- and Ti-tamped capsules are shown in Fig. 2. We clearly note that in both cases the integrity of the shell is preserved with Ti appearing to be a better tamper giving a reduced mixwidth. A Fourier analysis of the pusher/tamper interface during the linear and mildly nonlinear phases indicates that an inverse cascade process is taking place. Shortest wavelength modes, with the fastest growth rates, initially grow until they reach saturation (growing linearly thereafter), giving way to longer wavelengths that dominate the spectrum. At late-time the spectrum shows considerable fluctuation levels and resembles a typical steady-state turbulence spectrum, i.e., one in which an inertial range at moderate wavenumbers separates the energy containing large structures from the shortest dissipation scales. To ascertain that our time-dependent flow has reached the turbulent state we employed the methodology and formulas described in Robey *et al.*[6]

[b] To avoid spurious boundary effects caused by the extent of the computational wedge, we limit the mode number content of the initial perturbation to contain only modes with integral number of half wavelengths. For the wedge chosen here only mode numbers in multiples of 6 are included.



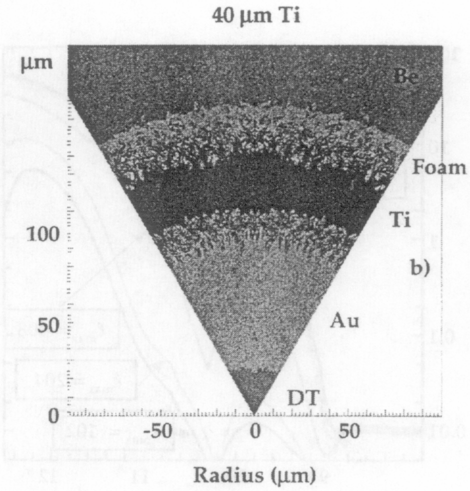


FIGURE 2. Material contours near ignition time with $l_{max} = 816$ for a) CH-tamped capsule of Fig. 1b b) Ti-tamped capsule of Fig. 1c.

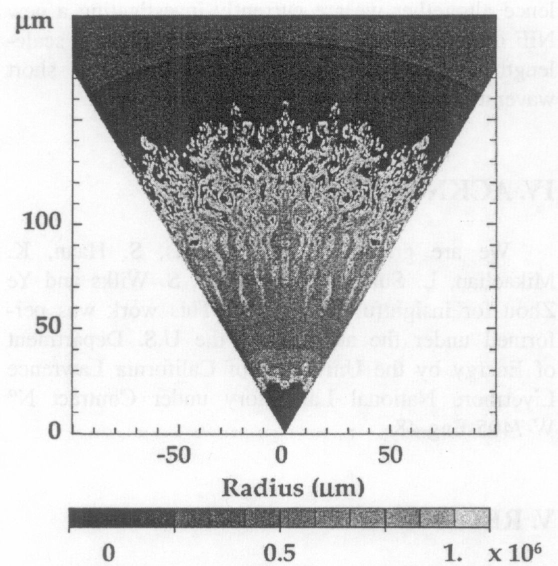


FIGURE 3. Reynolds number for the CH-tamped capsule with perturbation mode content $l_{max} = 612$.

For time-dependent flows to transition to a fully developed turbulent state (where mixing occurs at the molecular level) two conditions must be met. One necessary, but not sufficient, condition, established by Dimotakis[7], states that the Reynolds number $Re > 2 \times 10^4$. To this end, we have post-processed our calculations for the CH-tamped capsule with perturbation containing modes up to $l_{max} = 612$ and obtained at ignition time a value of Re ($Re = h\dot{h}/\nu$ where h and $\dot{h}$ are the size and time change of the mixing zone and ν is the kinematic viscosity) approaching 10^6 at the pusher/tamper interface as shown in Fig. 3. The second condition states that enough time (t) must have elapsed to allow for the appearance of an inertial range (L) defined as $50h/Re^{3/4} < L < 5\min(h/Re^{1/2}, (\nu t)^{1/2})$.[6] For the capsule of Fig. 3 we obtain $0.1 < L < 0.3$ μm. Our calculations are unable to resolve the full range of turbulent scales and so we expect that the details of the small scale-structure may not be strictly correct. However, we have confidence that the larger scale structures are well-resolved. Further support is found in the widely accepted fact that flows reaching the fully develop turbulent state exhibit small changes whether at $Re \approx 2x10^4$ or much higher. Additional confirmation of this fact is obtained by performing 2-D simulations of the capsule in Fig. 1b with perturbations that include modes ranging from $l_{max} = 102$ to $l_{max} = 1020$. The results of these simulations, shown in Fig. 4a, suggests that a mix-width of ≈ 50 μm is reached beyond 12 ns. Moreover, work by Dimonte *et al.*[8] indicates that for a time-dependent acceleration the bubbles of light fluid penetrate with an amplitude $h_b = 2\alpha_b AS$ where $S = 0.5[\int \sqrt{g}dt]^2$. Fig. 4b shows that by ignition time (≈ 12.5 ns) $\alpha_b \approx .062 - .067$ in line with rocket rig[9] experimental results. The mild time dependence of α_b is likely due to spherical convergence effects (see Mikaelian[10]) not present in the planar experiments.

Avoiding the possibility of developing a turbulent state allows us to have more confidence in our simulation results. To this end, we are investigating the target shown in Fig. 1d. It consists of an inner shell with a radially increasng Cu concentration (ranging from pure Au at the inner surface to pure Cu at the outer surface) in combination with a CuO/Cu_2O foam. This configuration enables us to significantly reduce the growth of high mode numbers by introducing a density-gradient scalelength. Two-dimensional simulations are under-

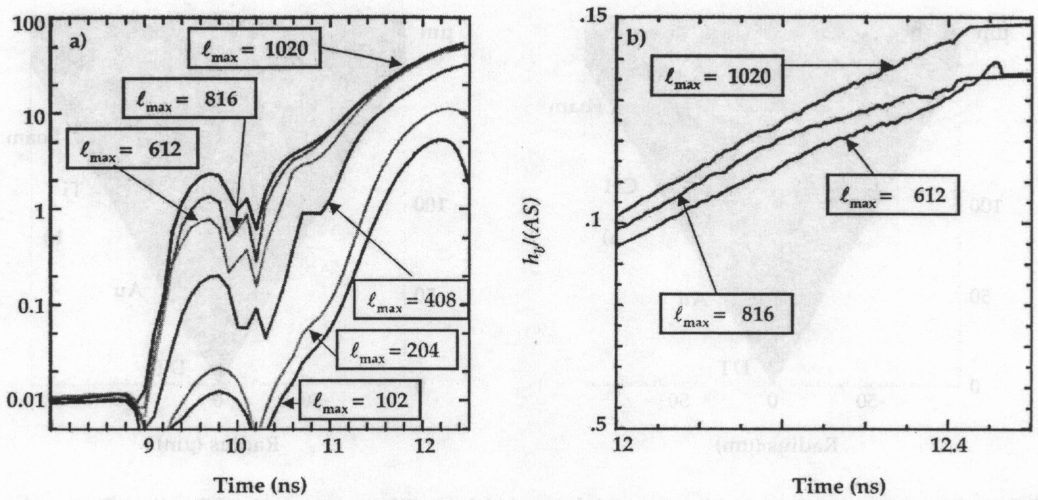


FIGURE 4. a) Calculated mix-widths vs time, b) Late-time behavior of simulated $h_b/(AS)$ vs time.

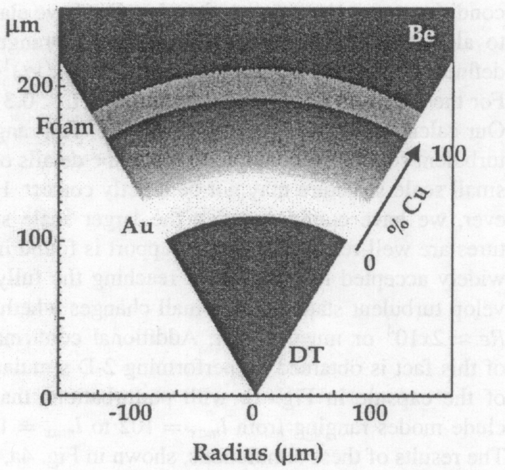


FIGURE 5. Material countours 250 ps before burn time for an initial perturbation containing modes up to $l_{max} = 612$.

way to assess the viability of this target. Figure 5 shows the behavior of the outer surface ≈ 250 ps before burn time for perturbations with $l_{max} = 612$, suggesting that our expectations are justified.

III. SUMMARY

We have studied RT instability of perturbation on the outer surface of the pusher and found that high growth may quench ignition. To control this instability we introduced a tamping layer which is able to mitigate the effects of mix. The mix-layer that develops reaches a fully turbulent state but simulations indicate that the inner shell remains intact. To avoid the onset of turbulence altogether we are currently investigating a new NIF design with an imprinted density gradient scale-length. Simulations suggest that the growth of short wavenumbers is substantially reduced.

IV. ACKNOWLEDGMENTS

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